

Approximate Modeling of Cylindrical Inertial Electrostatic Confinement (IEC) Fusion Neutron Generator

Blair P. Bromley, Luis Chacon, George H. Miley
Fusion Studies Laboratory, Department of Nuclear Engineering
University of Illinois at Urbana-Champaign
103 South Goodwin Avenue, Urbana, IL, 61801

The Inertial Electrostatic Confinement (IEC) cylindrical fusion neutron generator device (C-Device) is an elongated insulated vacuum chamber with an alternating series of hollow cylindrical cathodes and anodes spaced axially apart on a common longitudinal axis with solid end plates. The anodes, cathodes and end plates are biased to steady state and/or pulsed voltages. This configuration is used to initiate a plasma discharge and to create inertial electrostatic confinement of fusion fuel ions in both the axial and radial directions [1]. The IEC C-Device can produce neutrons from either deuterium-deuterium (DD) or deuterium-tritium (DT) reactions. Present operation produces about 10^6 n/s (DD) steady state while pulsed output at 10^9 n/s (DD) is under study. With such performance, the C-Device shows promise as a portable source for neutron activation analysis and neutron tomography.[2] In order to optimize the design and operating conditions of the C-Device such that the neutron generation rate will be maximized, an improved theoretical understanding of the plasma physics behavior is being developed through plasma simulation studies. The IEC C-Device is modeled with a computer code (C-Fusion) [3] that uses simplifying approximations and analytical expressions to treat the unique ion beam dominated plasma. Ultimately, a multi-dimensional, multi-species comprehensive model employing either particle-in-cell (PIC) techniques or kinetic theory (Fokker-Planck-Poisson equations) should be developed and combined with an extensive series of experiments to determine the optimum design of the C-Device. However, to gain a quick understanding of the effects of important performance parameters, such as voltage, current, pressure, temperature, and plasma beam size, the simpler C-Fusion model has been developed. Knowledge gained from the C-Fusion model will help guide future experiments as well as the development of more sophisticated simulation models.

The IEC C-Device is an electrostatic confinement system which ionizes the background neutral gas through electron and ion impact ionization, and then accelerates ions axially to a central core inside a hollow cylindrical cathode that exists between two hollow cylindrical anodes. Ions recirculate back and forth through the cathode between the anodes while electrons recirculate back and forth through the anodes between the end plates (reflectors) and the central cathode. Both ions and electrons continue to recirculate until they are lost to the electrodes or the vacuum chamber wall due to charge exchange and scattering collisions. The anodes create an electrostatic radial focusing of ions while the central cathode creates an electrostatic radial focusing of electrons. The combined axial acceleration and radial focusing causes the formation of a plasma beam in the C-Device. Fusion reactions are maximized in the hollow cathode region where fusion fuel ions are at their peak energy and density.

Several simplifying assumptions are made in the C-Fusion simulation of the IEC C-Device. The plasma is assumed to be locally quasi-neutral and hence there is a linear axial variation of the plasma potential throughout the device. Plasma properties are assumed to vary only in the axial direction. The plasma is comprised of only electrons and single deuterium ions, while the neutral background gas is treated as an ideal gas of monatomic deuterium and is uniform in pressure, temperature, and density throughout the device. All deuterium ions are assumed to be born at the anode and allowed to accelerate to their maximum kinetic energy, which is equivalent to their potential energy at the anode. The ion particle current flows primarily in the axial direction in the anode-cathode-anode region of the C-Device and is conserved. Ion particle conservation implies that half of the ion particle current flowing in the anode-cathode-anode region flows in one direction, while the other half flows in the opposite direction. This implies that the ion density in each counter-streaming ion beam is $n_{\text{ion}} / 2$ because the ion speed is transversely uniform at each axial position. The ion particle currents in the anode-cathode and cathode regions are related to the measured electrode electrical current by a recirculation factor ζ . The recirculation factor depends on the mean free path of ions in the C-Device and the distance between the anodes. The main type of collision which limits

the recirculation of ions is charge exchange because fast neutrals are lost to the reflector plates or the electrodes in a single pass. Thus, the charge exchange cross section σ_{cx} dominates in the calculation for the mean free path. The contribution of scattering (ion-neutral or Coulomb) to ion particle losses from the device is be minor when compared to charge exchange because the scattering angle is small. Fusion neutrons are generated by three main processes: beam-background reactions in which accelerated ions fuse with the background neutral gas deuterium atoms, beam-beam reactions in which counter-streaming ions fuse with each other, and fast-neutral-background reactions in which fast neutrals, created by the charge exchange of accelerated ions on the background neutral gas deuterium atoms, fuse with the background deuterium atoms. The fast neutrals are assumed to be travelling in the axial direction only, and have the same energy as the ions that created them. The generation of fusion reactions by deuterium ions and fast neutrals striking solid surfaces (such as the reflector plates) which have absorbed deuterium is considered to be insignificant compared to the other mechanisms described previously.

These assumptions allow the formulation of a relatively simple set of particle and energy conservation equations which can be used to test the scaling of various operational parameters and to perform parametric studies of the C-Device neutron generation rate for a range of operational anode voltages and currents. The model is not expected to be completely accurate because the approximations do not take into account the scattering collisions that do cause ions to be lost from the system, along with the axially distributed generation rate of ions due to electron-impact and ion-impact ionization. In addition, the assumption of local quasi-neutrality and no radial variation of plasma properties is inconsistent with a two-dimensional non-linear plasma potential profile that would occur in reality. The C-Fusion model also does not have a self-consistent solution for the plasma beam diameter. However, C-Fusion predicts the correct trends and gives a good estimate of the neutron generation rate in the C-Device at current experimental operating conditions (10 to 30 kV anode voltage, 10 to 40 mA electrode current, 0.29 to 1.1 milliTorr deuterium gas pressure) with an average accuracy of 65%. A semi-empirical correlation is developed to correct the global neutron generation rate prediction by the C-Fusion such that it will match current experimental results at low voltages and currents. This normalized C-Fusion model is combined with an empirical correlation of the operating deuterium gas pressure to obtain a prediction of the C-Device neutron yield at much higher extrapolated operating conditions (10 to 100 kV, 0.01 to 100 A). The neutron production efficiency is evaluated for experimental and extrapolated operating conditions, and the optimal operating conditions for maximizing the neutron generation rate (up to 10^{11} n/s) of the C-Device for its various applications are assessed.

References:

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